

CH-Section Focusing Solenoid with Dipole Corrector Windings

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Fine steering of a proton (or H^-) beam is required to reduce fraction of lost particles in the front end of a HINS linac [1]. Because the longitudinal real estate of the linac is heavily populated, combining dipole corrector windings with focusing lens seems an attractive option. Requirements for the correctors have been posted by P. Ostroumov in his E-mail of June 19, 2006: for the CH section they call for 0.25 T-cm of the integrated steering field. A way of how the correctors could be built has also been proposed by referring to [2], where corrector windings were placed above and below the focusing solenoid. Although quite feasible for other applications, this approach to combining focusing lens and steering dipoles is not a perfect solution in our case because of the presence of a magnetic circuit in the form of an iron flux return needed to reduce fringe magnetic field. While trying to find an appropriate solution for the problem, here we discuss two ways of how the corrector windings could be introduced. The first way uses the existing design of a CH section focusing solenoid while the second one requires some modifications to be made.

I. Corrector windings with the existing design

Schematic of the existing solenoid design [3] is shown in Fig. 1.

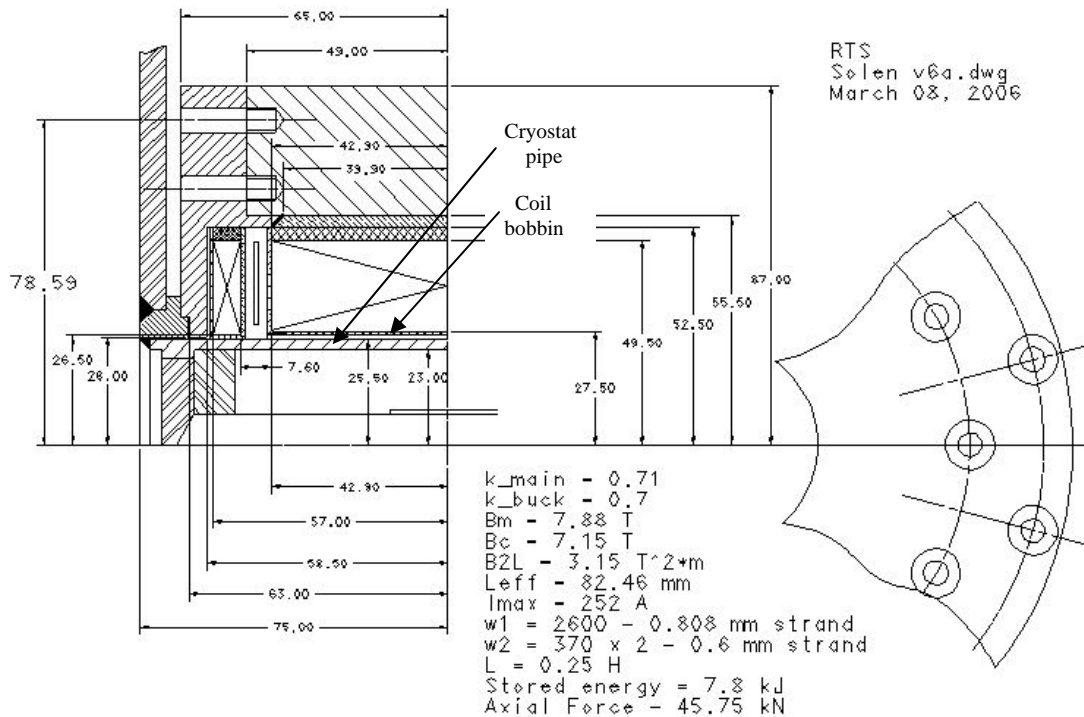


Fig. 1: CH-type section solenoid design concept

The requirement of having a 20-mm beam bore diameter in the CH section results in the outer radius of the solenoid cryostat pipe $R_o = 25.5 \text{ mm}$. A bobbin of the main coil is concentrically placed outside of this pipe. For better cooling of the inner turns of the coil, the bobbin is made of copper and equipped with channels (grooves) on the inner surface

for LHe penetration. Superconducting strands can be placed in these channels following a certain pattern to form windings of vertical and horizontal correction dipoles. One of possible patterns is shown in Fig. 2.

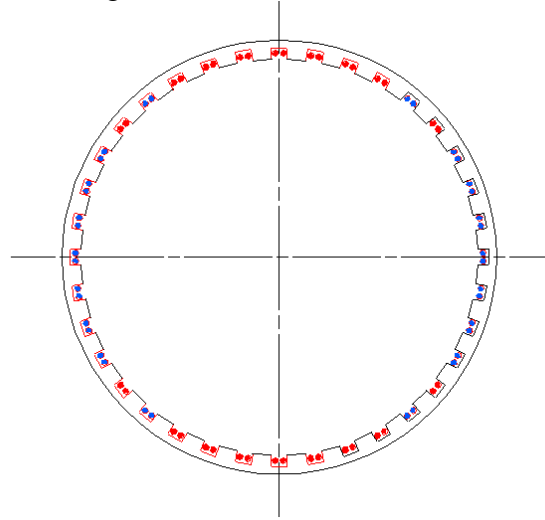


Fig. 2: Cross-section of a corrector dipole for the CH-type section

Here the total number of the channels is 36; each channel is 1.0 mm deep and 2 mm wide. In each groove, two strands are positioned: the strands marked red in the figure form a vertical dipole (it steers vertically); the blue strands form a horizontal one. For both the vertical and the horizontal dipoles, arrangement of the turns is close to a “cosine-theta” pattern, which helps to obtain reasonably good field quality. Placing the windings inside the solenoid has its good and bad sides: small aperture of the dipole helps to reduce amount of material used for winding, while the magnetic field of the solenoid limits the achievable current density in the strands. If a 0.8-mm NbTi strand is used to make the correctors (this strand was used in the main coil), the maximum current is 250 A, the quench current of the solenoid [3]. Some results of 2D modeling are shown below.

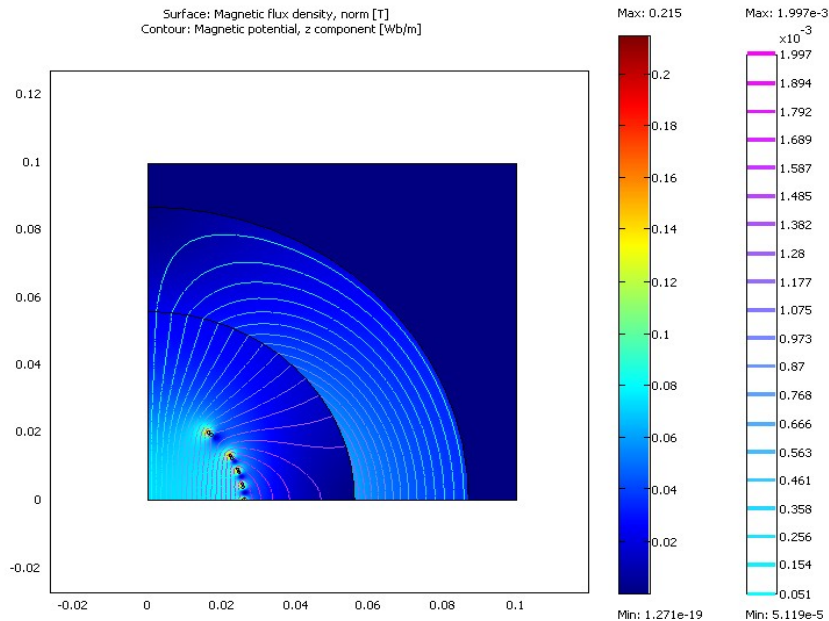


Fig. 3: Field map for the horizontal correction dipole (COMSOL)

Fig. 3 shows a field map for the horizontal dipole with current in each strand (two strands per turn) of 250 A. Field lines outside the dipole are contained by the solenoid's flux return. To take into account that the flux return is already "loaded" with the field of the solenoid, during the modeling relative permeability of the flux return material of 10 was used. The field inside the bore is quite uniform, which is the result of a "cosine-theta" arrangement of the winding. Non-uniformity is about $\pm 3.5\%$ in the full aperture of the solenoid bore (20 mm). Fig. 4 shows magnetic field distribution in the horizontal and vertical planes.

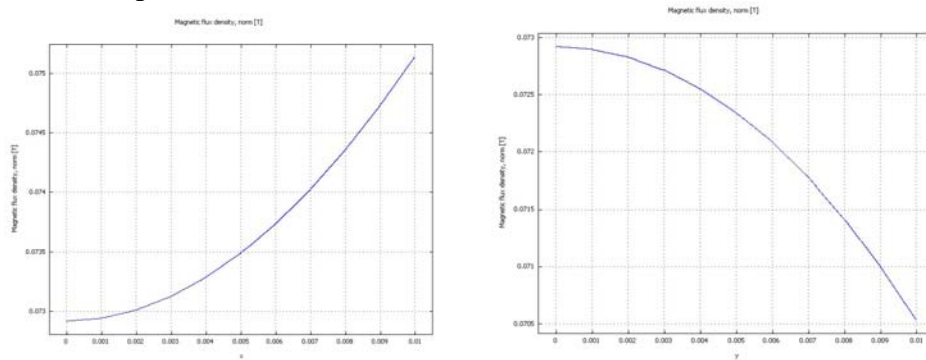


Fig. 4: Distribution of magnetic field in the horizontal and vertical planes

At 250 A, magnetic field on the axis is ~ 0.073 T. The length of the slotted copper cylinder of the bobbin is ~ 8.5 cm, so the expected integrated strength is ~ 0.6 T-cm. This is about twice as much as what is required, so making this type of correction windings inside the solenoid for the CH-type section looks feasible even with only one strand in each groove of the bobbin.

After a design solution has been found on how to make the winding, it has been introduced into a "Prototype-2" solenoid to get practical experience of making the windings and to test how it works. Implementing this type of a correction winding was quite straightforward and successful in the end, but labor-consuming in forming the ends of correctors and making current leads. The complication was mainly due to quite limited space between the main and the bucking coils. Because of a quite high magnetic field in this area, each turn must be properly insulated and fixed firmly in its channel.

A photo of the winding's end arrangement, made in a gap between the main coil and the bucking coil, is shown in Fig. 5.

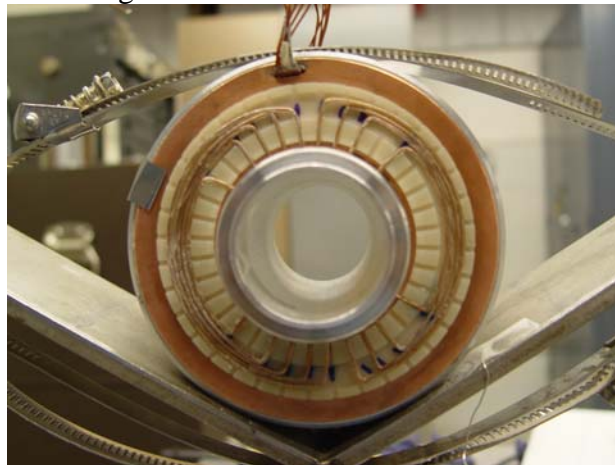


Fig. 5: End arrangement of a corrector dipole

II. Modified design of a solenoid with corrector windings

Because of the labor-consuming experience during fabrication of the Prototype 2, another approach has been developed that makes assembling the system easier. This approach suggests independent fabrication of a main coil, bucking coils, and corrector windings; a cold mass is assembled then by using the preassembled components. Fig. 6 provides a sketch of the system.

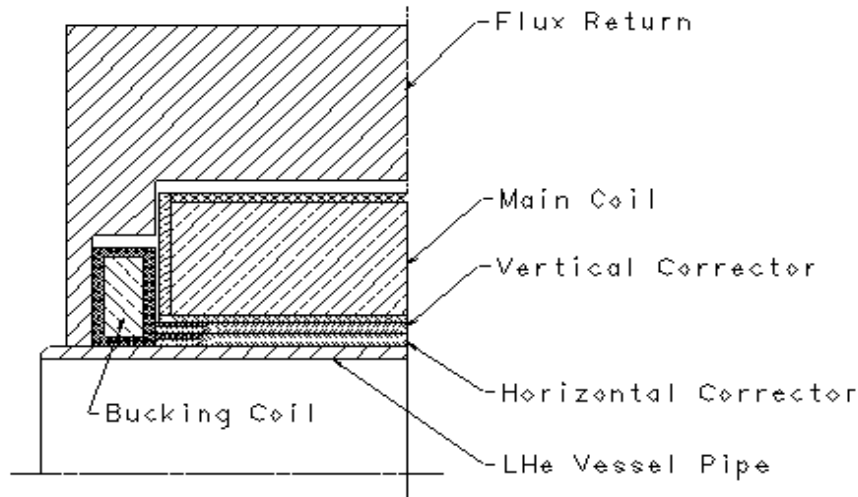


Fig. 6: Modified design of a focusing solenoid with dipole correctors

Each of the correctors is wound on the outer surface of a G-10 cylinder by using superconducting strand of appropriate size. The assembled correctors and the main coil are arranged coaxially to form one sub-assembly. Leads of the correctors are coming out between the main and the bucking coil. In this case, the solenoid design needed some changes because additional radial space was required (the inner radius of the main coil can not be made less than 32 mm).

A table below contains updated parameters of the system.

Main coil length (mm)	44
Main coil thickness (mm)	22.5
Main coil number of turns	2954
Bucking coil length (mm)	7.5
Bucking coil thickness (mm)	16
Bucking coil number of turns	318
Gap between the main coil and the bucking coils (mm)	5

Magnetic modeling was made to understand whether the design can meet the technical requirements for the lenses and correctors. Main results of modeling are shown below for the modified lens and for the corrector windings.

1. Modified Lens

Fig. 7 shows a field map for the lens of the device.

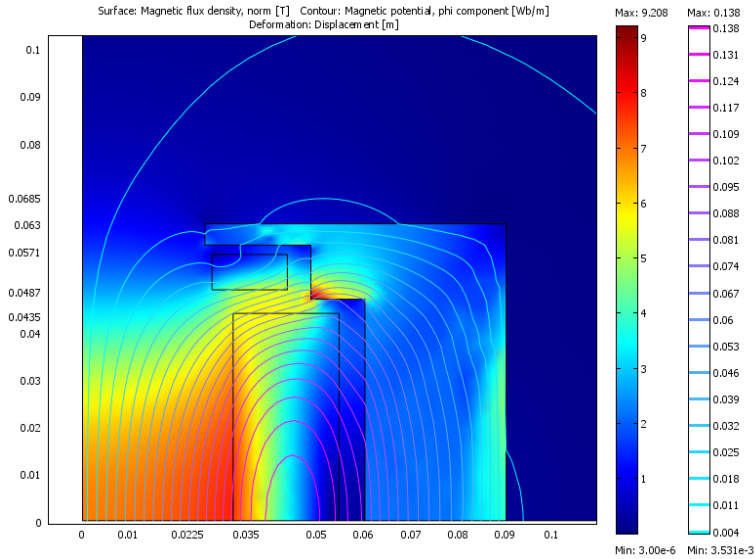


Fig. 7: Field map of a focusing lens at quench current (221 A)

Although some improvement of field quality can be made if to increase the radial size of the bucking coils, lesser radial thickness presents some advantages for fabrication, allowing making more compact winding. After modification, slightly different quench current is expected for the main coil and bucking coils as it is illustrated in Fig. 8.

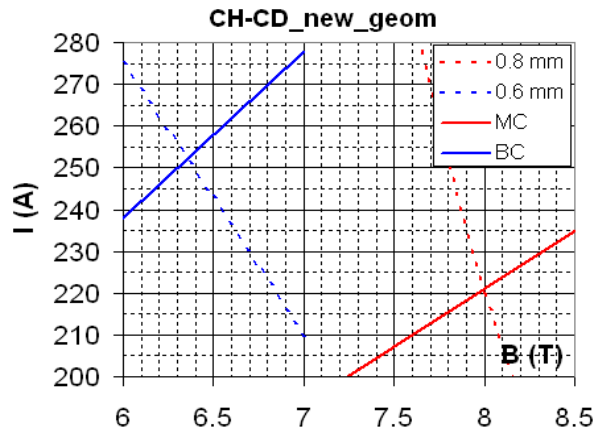


Fig. 8: Quench diagram of the focusing solenoid

The current in the solenoid is limited by a quench in the main coil at 221 A; the bucking coil quenches at 253 A providing some operational reserve for these coils. Longitudinal field distribution is shown in Fig. 9:

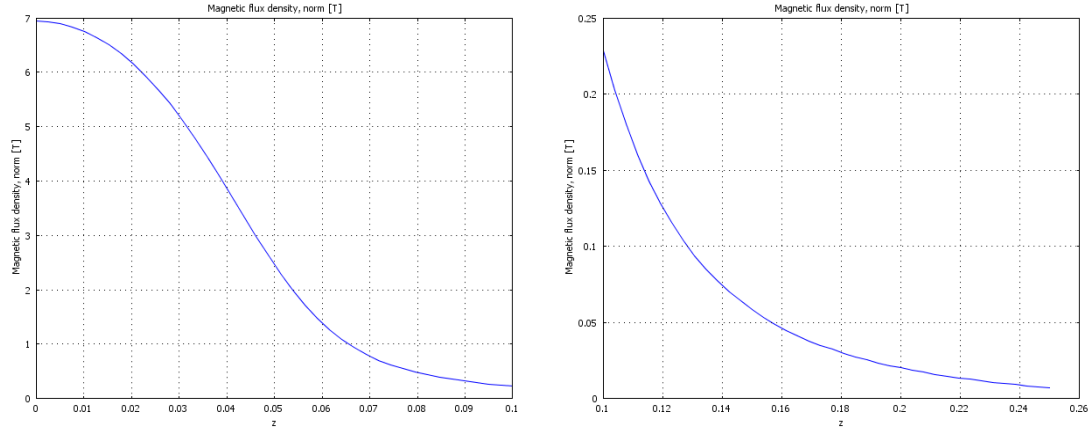


Fig. 9: Magnetic field along the solenoid axis

At 221 A, the focusing integral $\int B^2 dz \approx 3.2 \text{ T}^2 \text{ m}$; this sets the nominal current at 175 A to get $\int B^2 dz \approx 2 \text{ T}^2 \text{ m}$ with $\sim 20 \%$ current margin. The effective length of the solenoid is 88 mm, which is less than the specified 100 mm.

So, the modified solenoid meets the requirements for the focusing field.

2. Corrector

Geometry for a 3-D modeling of a vertical dipole is shown in Fig. 10.

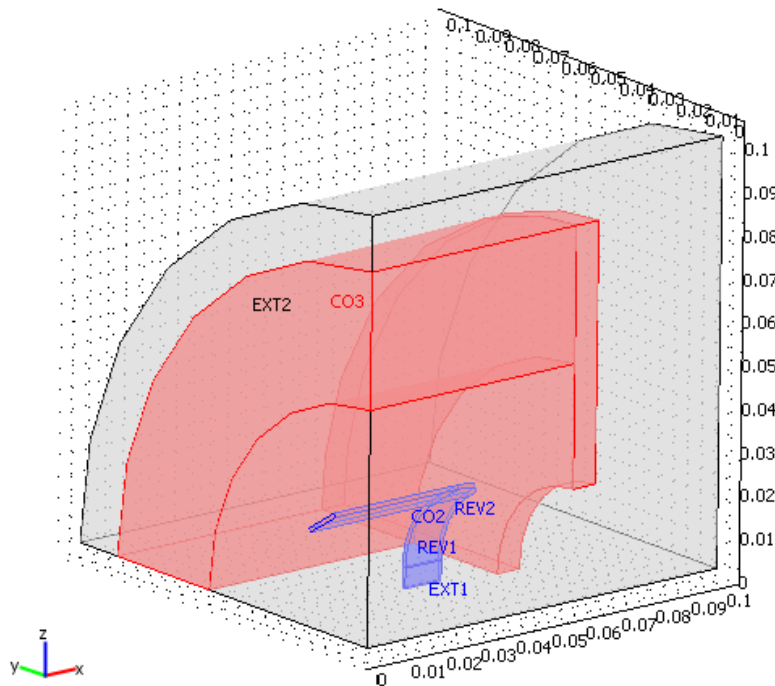


Fig. 10: Geometry for modeling of a vertical corrector.

Similar geometry was used for a horizontal corrector. The difference between the two correctors is in slightly different radial position of the windings and in the total number of turns, which is 18 for the horizontal corrector and 20 for the vertical corrector, which has larger radius.). 0.8-mm NbTi strand was used in both cases.

Fig. 11 shows magnetic field distribution for the horizontal corrector along the lines parallel to the solenoid axis.

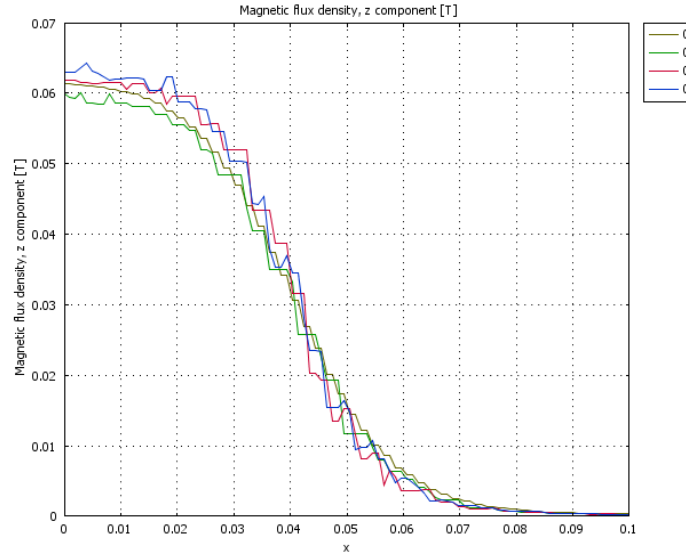


Fig. 11: Magnetic field profile for the horizontal corrector along the lines parallel to the system axis at 250 A.

The brown line represents magnetic field along the axis, the red line is for the pass which is 10 mm above the axis, the green line is for the pass which is 10 mm aside in the Y direction, and the blue line is for the pass which is shifted 7 mm horizontally and 7 mm vertically relative to the axis. So, the magnetic field is quite uniform within the beam line aperture. At 250 A, $\int Bdz \approx 0.51$ T-cm, which is consistent with what the first design, described earlier, provided.

For the vertical corrector, along the axis, at 250 A, $\int Bdz \approx 0.54$ T-cm, so for both correctors the requirement of having the integrated strength of ~ 0.25 T-cm can be satisfied at ~ 125 A.

III. Dipole Corrector Protection

This part of the note describes main features of a quench protection system that should be used during tests of a Prototype 2 of the CH solenoid (the one with the embedded corrector dipoles discussed in part I of this note).

During the testing, the two dipoles of the corrector (the vertical and the horizontal) will be connected in series. The dipoles are oriented perpendicular to each other, so there is no inductive connection between them. So, the combined magnetic field is in the plane that is rotated 45 degrees to the plane of each dipole and the total inductance is a sum of the inductances of the two windings.

Inductance can be evaluated by approximating the shape of the winding to a cylinder with the diameter $d = 50$ mm and the length $l = 40$ mm. Then the inductance of each winding is:

$$L \text{ (nHn)} = (\pi \cdot N \cdot d)^2 / (l + 0.45 \cdot d),$$

where d and l are in cm.

This results in the inductance of the two windings $L = 3.5 \mu\text{H}$. The energy stored in the correctors at 250 A is then ~ 0.22 J.

The total length of the strand in the windings is ~ 7 m and the total mass of the strand is ~ 30 g. This means that the energy per one gram of the strand is ~ 0.007 J/g. This

energy deposition will not result in any significant temperature rise if a power supply is off immediately after a normal zone is recognized.

While planning a test of the Prototype 2, use of only one power supply was considered first and we planned on connecting the correction dipoles and the solenoid in series. In this case, at 250 A, all the energy stored in the solenoid, that reaches 5.5 kJ, is deposited in the correction windings and the average energy deposition in the winding becomes ~ 200 J/g. This would result in the average temperature rise of $\sim 300^\circ\text{C}$, which seems unacceptable. **So, the correction winding must be powered separately.**

The next question to answer is how quickly one needs to react to switch the power supply off after a quench condition is registered. A quench propagation velocity can be calculated in adiabatic regime using the expression available from [4]:

$$v = \frac{J}{\gamma \cdot C} \left[\frac{\rho \cdot k}{T - T_0} \right]^{1/2}$$

At 150 A of current in the correction windings, at 8T magnetic field, a quench propagation velocity is ~ 150 m/s. This means that in the worst case it will take ~ 40 ms for the winding to turn normal. Energy required to heat the corrector windings up to 300 K is ~ 3 kJ. At this point, resistance of the winding will be ~ 0.5 Ohm. Assuming the linear growth of the resistance with time, we have ~ 0.25 Ohm average resistance, and at 150 A the average energy deposition rate will be 5.6 kW: so one should expect ~ 3 kJ to be deposited in ~ 0.5 s. This time of the system reaction seems marginally acceptable.

Voltage generated during quenching can also be estimated in a similar way. The voltage grows approximately linearly from 0 to $U_m = 150 \text{ A} \cdot 0.5 \text{ Ohm} = 75 \text{ V}$ (we do not take into the account the current source voltage limit of $\sim 40 \text{ V}$). So, the level of 1 V (which is quite sufficient for the quench indication) will be reached in ~ 7 ms. During this time the energy deposited in the winding will be of the order of $\sim 10 \text{ J}$ (resistance is $\sim 0.05 \text{ Ohm}$), which is considered safe.

References:

1. B. Mustapha, et al: Misalignment errors and Correction in the FNAL-PD Linac, Report to HINS R&D Meeting, Nov. 09, 2006, <http://tdweb.fnal.gov/HINS/MeetingMinutes/2006/>
2. P.N. Ostroumov, et al: A New Generation of Superconducting Solenoids for Heavy-Ion Linac Application, LINAC-2002, Proceedings, p. 332 – 334;
3. G. Davis, et al: Linac CH-Type Cavity Section Focusing Solenoid Cold Mass Design, TD-06-020, FNAL, 2006
4. M. Wilson, Superconducting Magnets, Oxford University Press, 1997, p. 206.